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THE DEVELOPMENT OF A TECHNOLOGY PRIZE TO PROMOTE ON-ORBIT SERVICING INFRASTRUCTURE

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OOS is an enabling technology for space infrastructure development and is closely linked to humanity's ability to further explore space. This paper documents the results of a two month, student conducted study that evaluated the potential use of a technology prize as a tool for spurring development in the OOS market. The goal of the project was to draw on existing technical and economic data of the satellite market and the state of current OOS capabilities in order to draw conclusions on how to best construct a technology prize. The study presents a brief overview of OOS, the challenges it faces in its development, the unique position a technology prize has in overcoming these barriers, and a conceptual framework for a collaborative OOS Prize. The OOS Prize proposed is based around the following points: develop OOS incrementally by focusing on near-term applications, use proven technologies or developed technologies, demonstrate a commercially viable service, and involve all relevant stakeholders at some level. The study revealed that there are no current technological infeasibilities with OOS and the lack of development is the result of uncertainty on the impacts of OOS capabilities on current operating methods. A technology prize for the development of a financially sustainable commercial OOS capability is one potential solution to this problem.

I. INTRODUCTION

The name they gave it was clever: ZombieSat. What was an amusing summer flick for the general public was a real-life nightmare for satellite operators. As the unresponsive Galaxy 15 geostationary telecommunications satellite shambled through the geostationary arc, satellite operators were forced to conduct a delicate ballet to prevent their signals from being interfered by the rogue satellite [1]. The ongoing ZombieSat episode highlights a critical loophole in the satellite community's ability to sustainably maintain and decommission their fleets. The on-orbit servicing of space assets provides a method for correcting satellite failures such as ZombieSat and extending the lifetimes of operational satellites; however, this capability does not currently exist due to a variety of barriers to development.

Overcoming the barriers to development for On-Orbit Servicing (OOS)* capabilities may be possible through the introduction of non-traditional technology development methods such as technology prizes. The technology prize concept has been used a number of times in the past to great success. Notable examples include the Orteig Prize which drew Charles Lindberg across the Atlantic and the Ansari X Prize which led to the development of SpaceShipOne. Prizes are a unique tool to develop technologies that are out of scope for government or free markets. Technology prizes have the advantage of taking radical steps; transferring, spreading, and reducing risk; spreading costs; growing community; and drawing together stakeholders [2] [3].

In the case of OOS, a technology prize holds the potential of expanding and uniting the OOS community around a common goal while building a framework for future collaboration. In addition, the prize could create an artificial demand for servicing, thus lowering a barrier that has previously prevented demonstrations of capability. In order to demonstrate the potential for a sustainable servicing capability, it is suggested that the OOS Prize include an actual servicing mission, on an actual satellite in space at a commercially viable cost.

The OOS Prize Study was a two month, student-conducted project at the International Space University (ISU). The mission of the OOS Prize Study was to create a conceptual sketch of a technology prize to promote the cooperative growth of commercial OOS infrastructure. The study supplemented existing research of OOS technologies, the satellite market, and technology prizes with interviews of members of the X Prize Foundation and NASA Centennial Challenges. The study was limited by the time available and the experience of the researcher; it represents a first step in the process of creating a collaborative effort to advance the state of OOS technologies and capabilities.

The intention of the OOS Prize Study was three-fold. First, as a student project, the study was intended to increase the student's understanding of and contributions to the field of space infrastructure development. Second, the study attempted to create a common goal for near-term OOS collaboration which

*OOS is also referred to as In-Orbit Servicing (IOS).

can be shared and advanced by the relevant stakeholders. Lastly, the study was intended to promote further discussion on non-traditional methods for developing sustainable OOS technologies and capabilities.

This paper presents a brief overview of OOS, the challenges it faces in its development, the unique position a technology prize has in overcoming these barriers, and a conceptual framework for a collaborative OOS Prize.

II. OOS OVERVIEW

II.I Definition of On-Orbit Servicing

The On-Orbit Servicing (OOS) of space assets is a broad concept that has been loosely defined by various groups throughout the Space Age. In some circles, OOS includes the assembly of space structures such as the International Space Stations (ISS), while others view assembly as a separate process. Other examples of such give-and-take definitions exist. The OOS Prize Study chose to adopt and adapt a definition of OOS proposed by international consultant Joerg Kreisel [4]. In this study, OOS is defined as all types of in-space servicing of space assets through human supported or autonomous means. In this definition, "in-space" is restricted to orbits around planetary or stellar bodies and excludes operations performed on the surface of a gravitational body. "Servicing" operations can be scheduled or emergency and performed by humans, robots, or the two operating jointly. "Space assets" are considered to be man-made objects, including satellites, space stations, spaceships, etc. The definition excludes the assembly or manufacturing of space assets, which are separate capabilities, enabled by the same technologies that allow for OOS. This definition allows for several unique OOS services to be identified and described.

II.II OOS Services

As defined by Kreisel, there are eight individual services provided by OOS, divided into three broad classifications [4]. In each, the service is performed on a client satellite by a servicer satellite. The Observation class involves the servicer gathering information from its client without contact (remote observation). The Motion class involves the servicer modifying the orbit of the client to either restore its position (re-orbit), locate it to a new orbit (salvage), or retire it (de-orbit). The Manipulation class involves the servicer performing modifications to the client (maintenance and repair), upgrading the client (retrofit), or gathering information directly (docked inspection). The services are not necessarily mutually exclusive, and a servicer satellite that can re-orbit a malfunctioning satellite will most likely be able to remotely observe, salvage, and de-orbit the satellite as well.

	Observation	Motion	Manipulation
Remote Inspection	X		
Re-Orbit		X	
De-Orbit		X	
Salvage		X	
Maintenance			X
Repair			X
Retrofit			X
Docked Inspection			X

Table 1: Individual OOS Services by Class [4].

Each of the eight services has a different degree of required technical development, required resources to perform, difficulty to perform, and returned value to the client satellite [5]. In addition, each class requires a different level of cooperative satellite design: Manipulation requires cooperative satellite design, Observation does not, and Motion does not but would benefit from it [4]. The full implication of each service is important to consider, as different stakeholders in OOS will be willing to support the development of different services for these reasons.

II.III OOS Stakeholders

The community of stakeholders in the development and operation of OOS capabilities is large and diverse; it covers nearly all fields in the exploration and development of space. The stakeholders are highly interconnected and have very different interests and intentions when it comes to the development of OOS capabilities. In part because of this, development of OOS technologies and capabilities has been fragmented and hesitant, with players often having different goals for the final product [6].

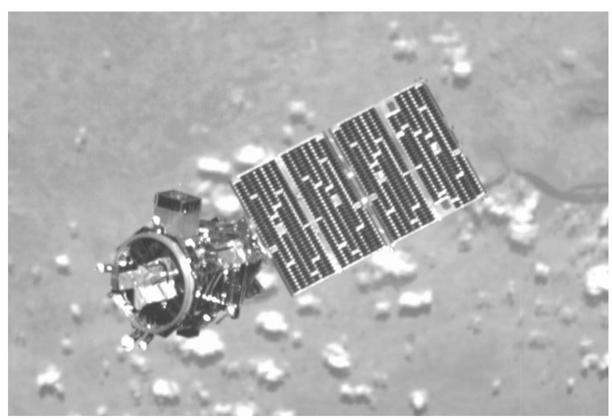

Fig. 1: An image of the NextSat client satellite. DARPA's Orbital Express mission demonstrated numerous, autonomous and controlled OOS systems capabilities. [Source: DARPA]

In this study, the OOS community was broken into six distinct groups. The first are satellite operators who own and/or control satellites. The second are satellite manufacturers who design, build, and test satellites. The third are launch service providers who place satellites into their orbits. The fourth are insurance brokers and financers who share in the risk of satellite programs. The fifth are national and international governments and agencies that oversee and manage operations to, in, and from space. The last group is the public who indirectly fund and benefit from the services provided by satellites [6]. The challenge faced by an OOS Prize is to bring this diverse community of stakeholders together to begin positive, cooperative development of sustainable OOS capabilities.

In general, satellite users benefit most from OOS capabilities. This includes operators, service providers, insurers, and end users. OOS has the benefit of ensuring data continuity, revenue streams, and service level agreements while lowering Capital Expenditure (CAPEX). On the other side, it is the enablers of satellite assets that risk most with OOS capabilities. This includes satellite manufacturers, launch providers, and regulatory groups. OOS forces a change in established practices, and these groups could possibly incur the largest costs to accommodate the change. These are not strict descriptions, however, and hesitation exists in all groups due to the fundamental changes in operations that OOS capabilities would introduce [6].

II.IV Advantages and Disadvantages of OOS

The OOS concept has gone through years of slow development due to the numerous potential benefits and drawbacks it brings to the space development community. The advantages of OOS over its alternatives have been theorized by several researchers, and a number of possible benefits are as follows: increased mission flexibility, responsiveness, and adaptability; increased mass allocation to payloads; reduced development time and costs through reducing redundancy; reduced integration &testing time and costs through standardized components, modules, and interfaces; reduce lifecycle & programmatic costs through the reuse and refurbishment of existing space assets; reduction in insurance claims and amounts; orbital debris reduction and removal; and an increased pace of technological development. By and large, the main benefit of OOS is its place as an enabler of more advanced processes such as autonomous assembly and manufacturing [5] [6].

While there are many benefits, the OOS concept also suffers several drawbacks due in part to the revolutionary capabilities it offers and the uncertainty of the impact of these capabilities. The disadvantages of the development of OOS capabilities have been theorized by several researchers and could possibly include the following: increased dependence on infrastructure; increased dependence on cooperative satellite development; reduction in satellite and launcher demand; increase in satellite systems cost through funding infrastructure; obsolescence of satellite technology before EOL; increased risk of damage from servicing; orbital debris creation; increased national security risks; and increased need for Space Traffic Management (STM) and other international cooperation. Like the advantages, the disadvantages of OOS are speculative. It is this speculative nature of the impact of OOS that has led to many of the barriers to its future development [5] [6].

II.V Barriers to OOS Development

Viewing the eight individual OOS services in light of the theoretical advantages & disadvantages of OOS and the relationships between the stakeholders, several barriers to further development can be identified. Based on research from several sources the OOS Prize Study identified eight key barriers to the development of an operational OOS capability [5] [6] [7] [8].

Lack of Proven Demand and Capability

In spite of the theorized benefits of OOS, its advantages and disadvantages have yet to be proven in an operational capability. The uncertainty of the nature of OOS services and their true impact on the space development community also make difficult the prediction of the cost of and returns from individual OOS services. Therefore demand for OOS demonstrators remains low. The result is a "chicken and egg" scenario whereby demand for OOS services is low due to a lack of an operational OOS capability, which is the result of a lack of demand for OOS services [6].

Fragmented Development Efforts

As mentioned previously, the stakeholders in OOS represent a diversity of interests. The result is various groups working on different technology programs with different goals. Standard designs for satellite components, interfaces, docking mechanisms, etc. are not under development to the degree required for extensive OOS capabilities. Stakeholders are hesitant to adapt proven designs and share design details among competitors to create standards for an unproven concept.

Cost of Developing an Operational Capability

A commercially viable OOS capability would involve significant investment in research, development, and deployment of interconnected ground-based, space-based, and network-centric projects. Such developments are beyond the scope of any single commercial company or government to develop, and stakeholders are hesitant to be the first to invest in the unproven concept.

Proven and Established Alternatives

Five current alternatives to OOS exist [6]. They include the use of redundancy and margins to guard against spacecraft failures; technical or software workarounds to fully or partially recover from satellite failure; abandonment for insurance claims; operational concepts such as on-orbit or on-ground spare satellites; and emerging concepts such as swarm satellites. The advantage of these concepts is their low risk when compared to developing an operational OOS capability; however, as the rate of satellite failures and space debris increase, their effectiveness comes into question.

Low Readiness Level of Certain Technologies

In a 2000 report by the United States Air Force Research Lab (USAFRL), it was found that “there appear to be no ‘show stoppers’ as far as technologies, to the implementation of space logistics and a support infrastructure” [7]. While OOS technologies appear within the reach of humanity’s current understanding of science and engineering, design and testing of these technologies has yet to be undertaken, preventing their readiness level from advancing. Several key technologies in need of development include the following: man-machine interfaces; machine-machine interfaces; standard docking mechanisms; sensors and data fusion; robotic and intelligent systems; fault detection, diagnosis, and interrogation.

Non-Accommodating Satellite Architecture

Multiple aspects of the current satellite design and operations paradigm present a barrier to implementing OOS capabilities. These include but are not limited to the following: non-compliance of current satellites with OOS, non-existence of industry standards; inflexible business models; inflexible launch services; and underdevelopment of Space Situational Awareness (SSA) and STM capabilities. OOS represents a large shift in the current view of operational space assets.

Non-Existent Regulations and Legal Framework

Current regulations and laws concerning the usage of outer space are built on a model where spacecraft interact with each other only by accident. OOS changes this model by introducing spacecraft which intentionally interact. This capability has serious implications on frequency allocations, liability, insurance claims, STM, debris mitigation, national security, and technology transfer among others. An immediate move towards this capability would require large investments in resources.

Other Priorities for Limited Funding

Present risk-capital is focused more towards projects with shorter pay-back times. This makes the OOS concept a very unlikely priority candidate as the time to prepare the satellites for capture (and therefore the first demands for a servicing operation) are cumulatively resulting in long investment periods and low Internal Rate of Return (IRR) values.

OOS development is therefore competing with other developments with shorter investment return perceived features. It is suggested, similarly to space tourism, to boost development via a technology prize mechanism, as will be described in the next chapter.

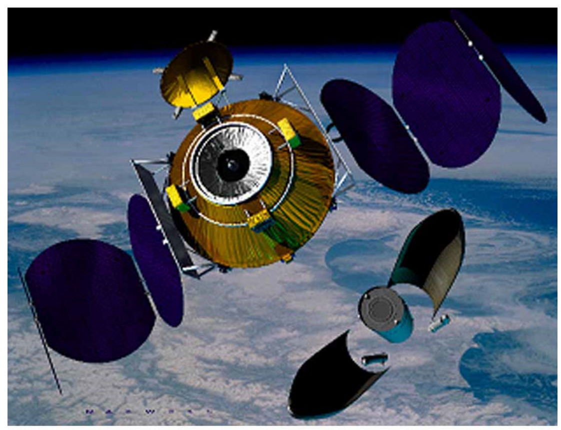

Fig. 2: Industrial and agency partnerships, such as the one behind the ConeXpress-Orbital Life Extension Vehicle, are attempting to demonstrate OOS services using near-term technologies. [Source: ESA and project team]

III. THE OOS TECHNOLOGY PRIZE

III.I Intended Consequences of the OOS Prize

With the barriers to developing OOS capabilities identified, the next step was to determine how a technology prize could overcome these barriers. The intended consequences of the OOS Prize should address each of the barriers as well as provide a basis for determining the framework of a conceptual prize. Based on existing research [4] [5] [6] [7] and interviews about technology prizes conducted with the X Prize Foundation [2] and NASA Centennial Challenges [3], the following seven intended consequences of an OOS Prize were determined.

Change Cultural Approach and Attitudes

In spite of successful technology demonstrations and commitments from national governments in the past decade, OOS concepts continue to be met with hesitation and scepticism by stakeholders. The positive momentum of these successes needs to be continued and built upon to demonstrate ever increasing capabilities. The OOS Prize shall take a large enough step forward to encourage a shift in attitude towards OOS, while not being too large to risk failures causing setbacks.

Involve and Influence Stakeholders

Development of OOS capability requires high amounts of cooperation from many stakeholders with diverse interests. Advances in operational OOS capabilities will require common standards, interfaces, regulations, and operations. Currently, efforts are hampered by fragmented and multiple projects by stakeholders. The OOS Prize shall lay the foundation for stakeholder cooperation by providing a common forum and goal for developing OOS capabilities.

Promote Incremental Development

Traditional views of OOS capabilities have included large investment in infrastructure such as on-orbit parts warehouses and fuel depots. While this may be the ultimate direction of OOS architectures, the cost and complexity of developing the associated infrastructure is prohibitive. OOS must be developed in steps to ensure that demand, markets, technologies, and regulations are developed concurrently. The OOS Prize shall build capability in steps by targeting near-term applications with near-term technologies.

Lower Barriers of Entry to OOS Development

In the last decade, numerous OOS servicer concepts have been proposed, including the ConeXpress Orbital Life Extension Vehicle (CX-OLEV), Geosynch Satellite Life Extension System (SLEV), among others. These programs feature technologies developed in national laboratories, but have yet to be demonstrated in-flight for lack of proven demand. This is the “chicken and egg” scenario of OOS [6]. The OOS Prize shall lower the barriers to entry for developing OOS capabilities by creating an artificial demand for an OOS service.

Develop Sustainable OOS Capability

The feasibility of the OOS system concept has been demonstrated by government agencies through several programs in recent years. These programs have neither sought to demonstrate an operational capability nor develop a capability that is profitable or cost neutral. In order for OOS to grow in capability in the long term, it must be designed to be economically self-sustaining, if not profitable. The OOS Prize shall promote capabilities that offer commercially viable services.

Establish Necessary Laws and Regulations

The laws and regulations governing commercial air and spaceflight have grown over time with incremental advances in capability afforded by new technologies. Similarly, customs, norms, laws, and regulations pertaining to OOS will develop as new capabilities are introduced. The OOS Prize shall establish the basic customs needed to ensure a safe competition while setting up the framework for positive, future developments in these fields.

Increase Investments in OOS R&D

The history of aerospace research is rife with programs that, having reached the end of their life, have yielded no follow-up developments. OOS is a system with diverse components from ground infrastructure to space assets to international forums. There exist many challenges to meet and many opportunities for various groups to be involved in the development of OOS. It is important that a diversity of voices and abilities are included in this process, and this is best done when OOS is funded and promoted in a positive way. The OOS Prize shall promote future interest and funding for long-term partnership and vision in the OOS community.

III.II OOS Prize Framework

Following the intentions of the OOS Prize, a framework for one possible prize was constructed based on a brief analysis of the satellite market. The conclusions of this section directly support one or more of the intentions, which in turn address one or more of the barriers to OOS development. The prize as conceptualized below would target Small and Medium Enterprises to perform a re-orbit of a GEO telecommunications satellite for a prize purse of between $25-$50m. In order to meet the intentions stated above, the OOS Prize Study suggested that the prize perform an actual servicing mission, on an actual satellite in space, at a commercially viable cost.

Who will compose the competing teams?

The technology prize concept has been successfully employed in the past to leverage the benefits afforded by small companies and groups of enthusiasts while excluding the complexities of working with larger organizations and government operations. The know-how, funding, and longevity of small companies and enthusiasts are widely variable; however they are able to achieve complex, innovative results at a fraction of the cost of larger groups. The growth of the CubeSat and Google Lunar X Prize programs has seen satellites and space robotics migrating into the hands of these smaller groups, enabling them to undertake an OOS servicing mission. The conclusion is that the OOS Prize would attract small companies, individuals, and universities for their capabilities and interest in exploiting niche markets.

Where are high-value space assets located?

The target satellite and its location determine the size of the servicer, the cost of the servicer, and the value of the service provided. As identified in Table 2 below, there are four orbital bands, each with four classifications of satellites, and two operators, resulting in 32 different operating scenarios for a servicer [6]. Selecting the appropriate target is critical in ensuring likelihood of success and commercial exploitation.

The terrestrial satellite population has exceeded 900 active satellites in recent years and continues to grow. Satellites are distributed unequally into the LEO/ SSO/Elliptical, MEO, and GEO orbits, as shown in Figure 3 below [9]. The most prominent satellites in LEO/ SSO/ Elliptical are earth observation, scientific satellites, and communication constellations with approximate yearly revenue of $1B in 2000. MEO is mainly composed of governmental systems such as GNSS with approximate yearly revenue of $4B in 2000. Finally, GEO/GSO orbits are populated mainly by telecommunications satellites with approximate revenue of $13.6B in 2000. An illustration of these amounts is seen in Figure 4 below. As of 2000, the GEO/ GSO bands contained 286 satellites with approximately 25 being decommissioned per year for reasons of propellant exhaustion [10].

Ideally, a servicing vehicle should be designed to cross several orbits to reach the largest number of clients. However, delta-v values for switching orbits are prohibitive, ranging between 100-500 m/s. Without the ability to refuel, the delta-v of switching orbits would require each orbit class to have its own servicer [10]. The conclusion of the above analysis suggests the OOS Prize should be targeted solely for a GEO telecommunications satellite.

Orbit	Satellite Type	Operator
LEO	Telecommunications	Government
SSO	Navigation	Commercial
MEO	Earth Observation	
GEO	Science	

Table 2: Satellite Operating Scenarios [6].

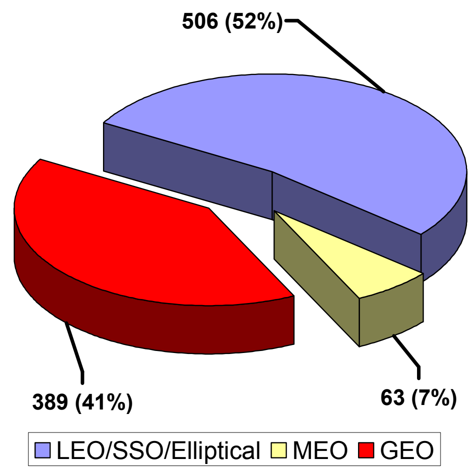

Fig. 3: Satellite Populations of Various Orbital Bands as of November 2010 [9].

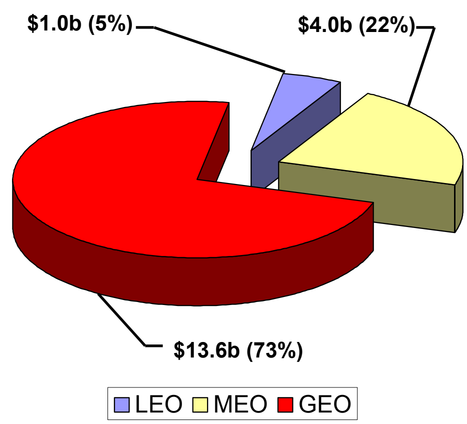

Fig. 4: Comparison of the Revenue from Various Orbital Bands as of 2000 [10].

How much might the servicing cost?

The value of a typical client satellite and the revenues the satellite generates in a year determine the limits on the price of a servicing event, and from this a range for the OOS Prize purse. Selecting an appropriate purse is critical for attracting the desired teams for the project's intent.

The recent trend in GEO telecommunications satellites has been towards larger, higher-valued assets representing increasingly larger revenues per satellite. A modern GEO telecommunications bus, such as the Boeing 702, carries between 60-80 transponders rated with yearly revenue of approximately $1.2m per transponder [10]. The cost of a typical GEO telecommunications satellite in 2002 was on average $250m corresponding to a yearly satellite revenue of approximately $42.3m [10]. A servicer launched today will more than likely be targeting aged satellites from this time period or earlier. Therefore, the price of the OOS service must be derived from several buses, containing various numbers of transponders, representing various revenue potentials per year.

A brief analysis of satellite values was undertaken to determine a range of possible OOS service prices. The calculations assumed that target satellites for OOS would range between 40 and 80 transponders, reflecting the trends of the past decade. As detailed by Ellery et al., the average annual revenue per transponder is estimated to be $1.2m [10]. This results in approximate yearly revenue of $48m for a 40 transponder satellite and $96m for an 80 transponder satellite. Figure 5 below compares the break-even times for three servicing prices for satellites of various numbers of transponders. The shortest time to break-even time is approximately one year for a $100m servicing price on an 80 transponder satellite. The longest time to break-even is approximately six and a quarter years for a $300m servicing price on a 40 transponder satellite.

A servicer mission to restore AOCS functions to a geostationary telecommunications satellite was suggested by the Orbital Recovery Corporation in 2002 [11]. The price of an affordable service for the client company was estimated to be between $50-$80m for a life extension of 4-7 years. In order for a profit to be realized by the servicing company, it was estimated that a servicer satellite would need to be constructed and launched for between $40-$70m [11]. The time to break even calculations for a service price between $40-$80m are shown in Figure 6 below. These figures suggest that original estimates between $100m-$300m are perhaps too high.

The conclusion of the above analysis on the size of the OOS Prize purse suggests an OOS servicer should be designed to service multiple buses having been launched over the last ten years with a servicing price of less than the studied $100-$300m range. If a prize purse is considered to be quarter of the final price of an operational service, then a $25-$50m purse would not be unreasonable based on previous studies.

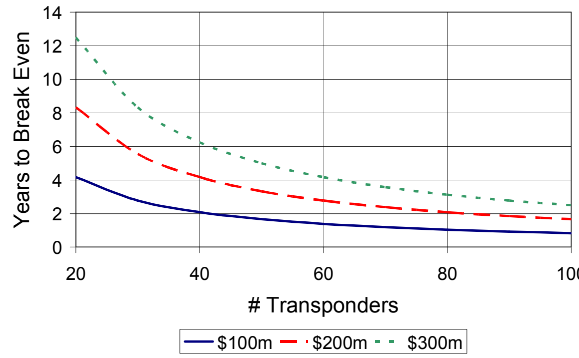

Fig. 5: Years to Break-Even for Transponder Count and Service Prices $100-$300m.

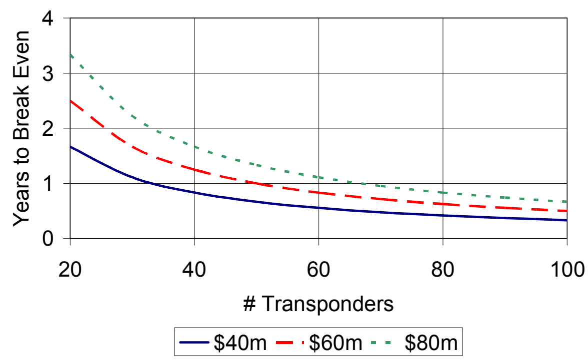

Fig. 6: Years to Break-Even for Transponder Count and Service Prices $40-$80m.

<u>What service should be provided?</u>

The types of spacecraft failures and the readiness of technology to address these failures determine the mission of the OOS Prize servicer. Failure modes for satellites can be broken down by subsystem and time of occurrence in the satellite's lifecycle. Failures occur most often on launch, during Beginning of Life (BOL), or during End of Life (EOL). Recent trends in satellite failures are showing a shift away from launch failures and into operational life failures. Satellite system costs and complexity are increasing, and for the first time in history, more satellites are failing as a result of in-orbit failures as opposed to launch failures [10].

Failures in the GEO telecommunications satellites have increased by 146% from 1996-2002. Satellite insurance rates have increased 128% from 7% to 16% of the satellite's cost in the same period, while insurance capacity has fallen from $1.3b to $900m. This represents a large shift in satellite insurance models as the traditional approach has been to set premiums based on launch failures, which are now the minority of instances [10].

Loss of AOCS, loss of propulsion, or improper orbit injection are some of the most common causes of spacecraft failure. These three failures can be remedied by Manipulation class services of a non-cooperatively designed target or Motion class services, with the later being less technically demanding. The drawback of using a Motion-based solution to restore satellite AOCS, propulsion, or orbit is that the servicer must remain attached to the client for the duration of the client's life extension. In the scope of the technology prize, where the intention is to make small steps using existing technologies to a one-time demonstration of an operational service, the permanent attachment of the servicer bus to the client is not a drawback. The conclusion of this discussion is that the OOS Prize Servicer should be designed to restore AOCS, propulsion, and orbit position to a satellite using the Motion class of services.

IV. CONCLUSIONS

The intention of this paper was to introduce the concept of using a technology prize to spur the development of on-orbit servicing capabilities. A brief overview of OOS, the challenges it faces in its development, the unique position a technology prize has in overcoming theses barriers, and a conceptual framework for a collaborative OOS Prize were presented. It was determined that the majority of barriers to the implementation of OOS capabilities stems from the uncertainty of the impact these capabilities would have on current satellite operations.

It was suggested that a technology prize would hold a unique position in overcoming these barriers. It was determined that the prize would appeal to small organizations to perform a re-orbit of a GEO telecommunications satellite for a prize purse of between $25-$50m. The study has not attempted to create rules or detail how the prize should be structured in order to accomplish these goals. In order to meet the intended consequences of the prize, the OOS Prize Study suggested that the prize perform an actual servicing mission, on an actual satellite in space, at a commercially viable cost.

As the paper stands, the OOS prize is only a brief conceptual analysis, with further investigation to be performed. Potential future work could include a detailed stakeholder analysis of the OOS community, an in-depth cost-benefit analysis of the various OOS services, updated information from the space insurance industry, an updated and broader study of satellite failures, and an investigation into methods and groups to host a technology prize for OOS development.

It is hoped that the OOS Prize Study will promote further discussion on non-traditional methods for developing sustainable OOS technologies and capabilities.

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